PHOTON PRODUCTION FROM NON-EQUILIBRIUM QGP IN HEAVY ION COLLISIONS

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- Expansion: boost invariant, ideal fluid hydrodynamics
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Photons

- Photon emission rates as a function of temperature and fugacities
- Integration over space-time evolution of temperature and fugacities

$\longrightarrow$ Photon spectrum

Equation of State and Fugacities

QGP is described as an ideal gas of massless quarks and gluons with bag constant B.

- Quark and Gluon densities are given by

$$(1)\quad n_i(T,\lambda_i) = \overbrace{\lambda_i}^{\text{fugacity} = 1 \text{ in equilibrium}} \underbrace{\hat{n}_i(T)}_{\text{equilibrium density}} = \lambda_i a_i T^3, i = q, g$$

- pressure and energy density are given by

$$(2)\quad \begin{cases} p = p_q + p_g - B = \lambda_q \hat{p}_q(T) + \lambda_g \hat{p}_g(T) - B \\ \varepsilon = \varepsilon_q + \varepsilon_g + B = \lambda_q \hat{\varepsilon}_q(T) + \lambda_g \hat{\varepsilon}_g(T) + B \end{cases}$$

- Hadron Gas = Ideal gas of massive hadrons with $m < 1.4$ GeV. We assume that HG is always in chemical equilibrium.

- Bag constant is obtained from phase co-existence condition:

$$p_{\mathrm{HG}}(T_c) = p_{\mathrm{QGP}}(T_c) = p_q(T_c, \lambda_q) + p_g(T_c, \lambda_g) - B(\lambda_q, \lambda_g)$$

We assume that $\mathbf{T_c}$ is constant independent of fugacities

→ Bag constant depends on fugacities

Test EoS: **no** bag constant, **no** Hadron Gas just (1-2) with B = 0

↔

Not strictly consistent with (1), but affects only low energy density part ($\varepsilon \sim B \sim 1$ GeV/fm^3) of QGP, while *photon emission* is dominated by the region where $\varepsilon > 100$ GeV/fm^3.

Hydrodynamics and Rate Equations

Expansion of the matter is described by boost invariant, ideal fluid hydrodynamics

$$(*)\qquad \partial_\mu T^{\mu\nu} = 0$$
$$T^{\mu\nu} = (\varepsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$$

Hydrodynamics equations are solved together with rate equations that describe time evolution of quark and gluon densities.

$$(**)\quad \partial_\mu(\lambda_i \hat{n}_i(T) u^\mu) = C_i(T, \lambda_g, \lambda_q)\,, \quad i = g, q$$

Rate equations are taken from the paper by Biró et. al.
Phys. Rev. C **48** 1275 (1993) [nucl-th/9303004]
where processes **qq ↔ gg** and **gg ↔ ggg** , that drive system toward chemical equilibrium, are included:

$$\begin{aligned} C_g &= \hat{n}_g R_3 \lambda_g (1 - \lambda_g) - 2\hat{n}_g R_2 \lambda_g \left(1 - \frac{\lambda_q \lambda_{\bar{q}}}{\lambda_g^2}\right) \\ C_q &= \hat{n}_g R_2 \lambda_g \left(1 - \frac{\lambda_q \lambda_{\bar{q}}}{\lambda_g^2}\right) \end{aligned}$$

$$\begin{aligned} R_2 &\approx 0.24 N_f \alpha_s^2 \lambda_g T \ln(1.65/\alpha_s \lambda_g) \\ R_3 &= 2.1\, \alpha_s^2 T (2\lambda_g - \lambda_g^2)^{1/2} \end{aligned}$$

Hydrodynamic equations (*), together with the rate equations (**) and **EoS,** give the time evolution of temperature and fugacities when the initial state is given.

Initial State

Initial energy and particle densities are obtained from **pQCD + saturation** model by Eskola et al.

Nucl. Phys. B **570**, 379 (2000) [hep-ph/9909456]

This model is in good agreement with measured hadron spectra at RHIC, when used as an initial state for hydrodynamic evolution.

Phys. Lett. B **566**, 187 (2003) [hep-ph/0206230]

see poster by S. Räsänen

We have to limit fugacities in order to get reasonable EoS so that QGP is stable phase at high-T and HG at low-T:

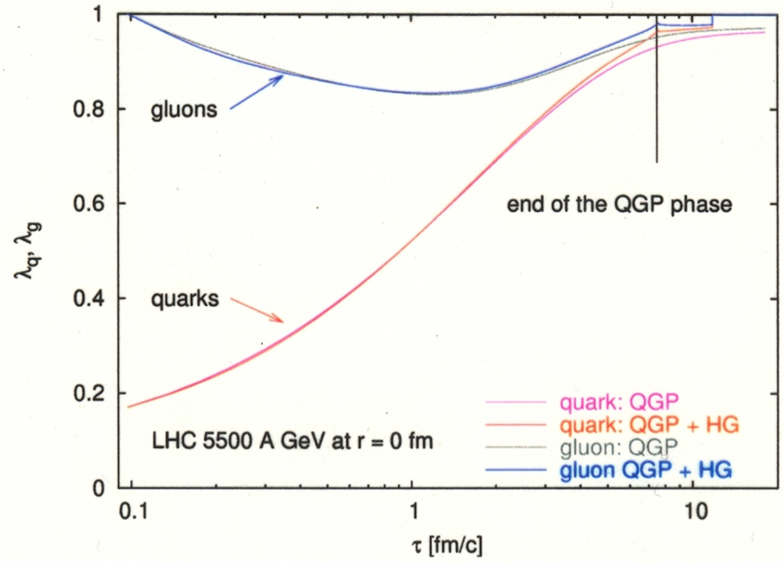
$$0.60 < \lambda_g < 1.0$$
$$0.17 < \lambda_q$$

Here we assume that initially $\mathbf{v_r = 0}$ and that $\lambda_q = \lambda_{anti\text{-}q}$

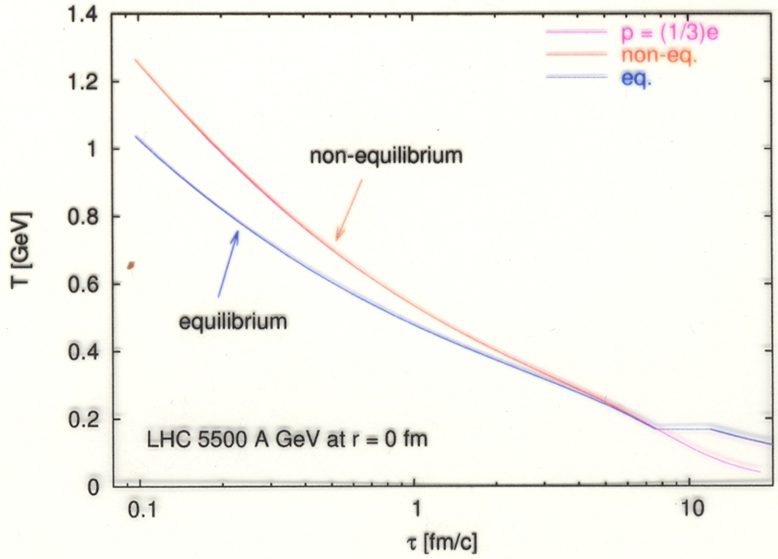
LHC 5500 A GeV:

$\varepsilon_{max} = 2350\ \mathrm{GeV/fm^3}$	$\tau_0 = 0.1\ \mathrm{fm/c}$
$n_{Q,max} = 148\ 1/\mathrm{fm}^3$	$\lambda_q(r = 0) = 0.17$
$n_{G,max} = 514\ 1/\mathrm{fm}^3$	$\lambda_g(r = 0) = 1.0$

Space-time evolution of temperature and fugacities



We are close to equilibrium at the end of the QGP phase.



At fixed energy density reduction of degrees of freedom is compensated by the increase in temperature

Average energy per particle is higher in chemically non-equilibrated system

Photon Emission Rates

- Space-time evolution of temperature and fugacities is known from hydrodynamics
- Photon emission rates in QGP and HG:

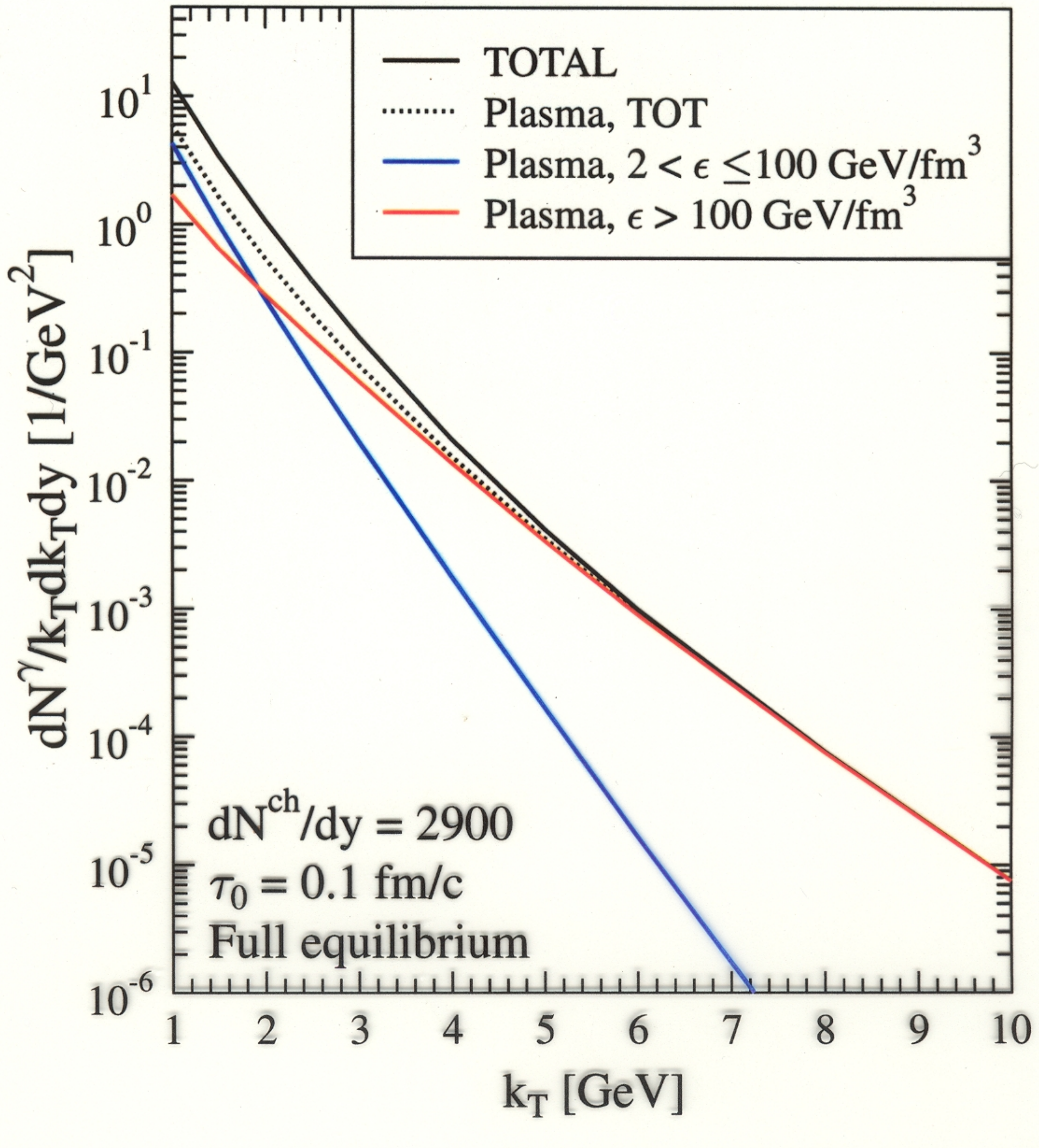
QGP: in chemical equilibrium: Arnold, Moore and Yaffe
JHEP **0112** (2001) 009 [hep-ph/0111107]
extension to non-equilibrium: Gelis, Redlich
[hep-ph/0311131]

Hadron Gas: equilibrium rates:
Kapusta, Lichard, Seibert
Phys. Rev. D **44** (1991) 2774
Phys. Rev. D **47** (1991) 4171
Xiong, Shuryak, Brown
Phys. Rev. D **46** (1992) 3798 [hep-ph/9208206]
Nadeau, Kapusta, Lichard
Phys. Rev C **45** (1992) 3034
Phys. Rev C **47** (1993) 2426

$$E\frac{dN_\gamma}{d^3\mathbf{k}} = \int d^4x \frac{dN_\gamma(\omega^*, T, \lambda_q, \lambda_g)}{d^4x\ d^3\mathbf{k}/E}$$

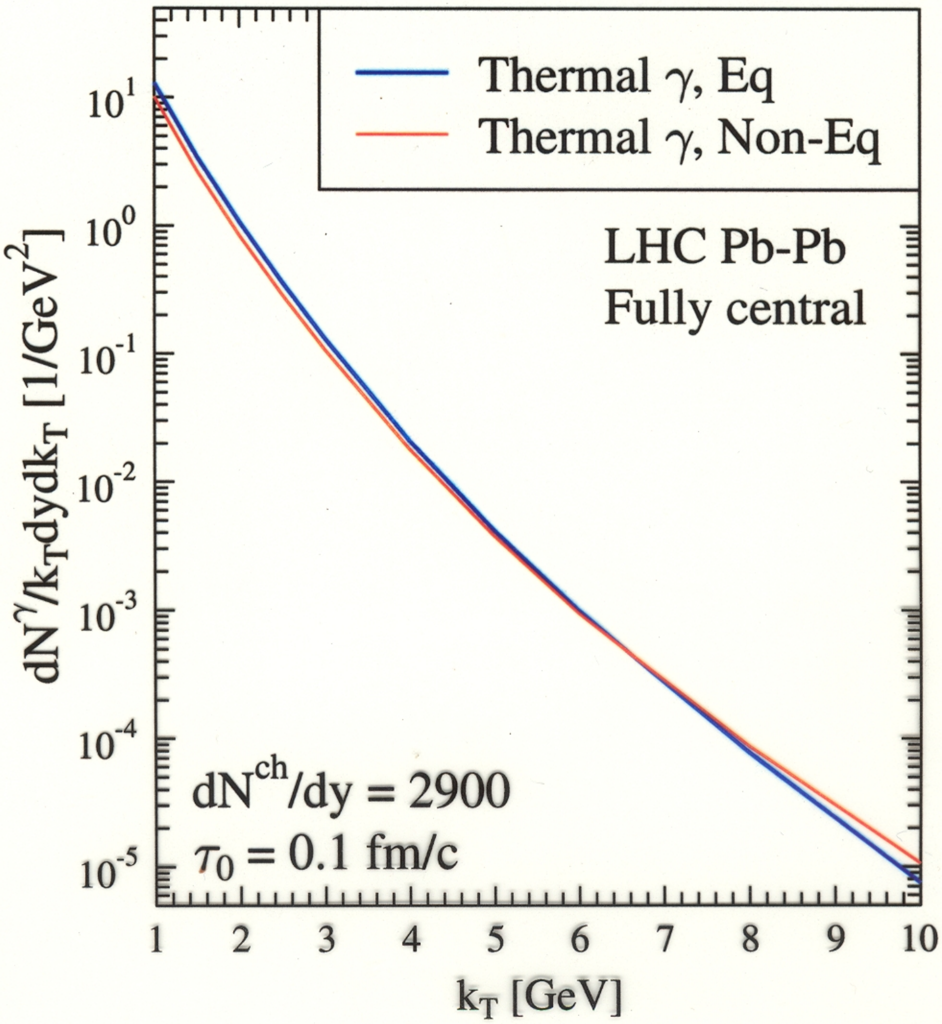
Integration over the space-time history of the collision.

Photon Spectrum I in chemical equilibrium



Thermal emission spectrum probes very early stages of the collision

Photon Spectrum II out-of chemical equilibrium



Altough $\lambda_q < 1$ reduces the number of emitters in QGP it also leads to a higher temperature of the plasma and these effect compensate each other.

Conclusions and Summary

- Large k_T photon emission is dominated by the emission from the very early stages of the collission.
- Altough number of degrees of freedom is less in chemically non-equilibrated system it has also higher temperature.
- These two effects cancel in thermal emission spectrum of photons.